MICRO FLOW PATTERNS ON DEMAND USING SURFACE-CHEMISTRY TECHNOLOGY

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ABSTRACT

A new technology to pattern surface charges, either negatively or positively, using a standard photolithography process is introduced. Unlimited flow patterns can be generated under an externally applied electric field by electro-osmotic and electrophoretic driving forces to enable fine control of fluid motion in microfluidic devices. Two basic flows, shear and vortical, have been realized experimentally to demonstrate the tremendous potential of this technology, especially in analytical microsystems for genomics or cell biology.

INTRODUCTION

Micro-fluidic devices have recently received significant attention since many applications in biotechnology involve manipulation of small objects, e.g. DNA or protein molecules, in fluid media. These applications motivate the development of technologies for driving and controlling fluid motion on a microscale.

One of the keys to manipulate microscale fluid fields hinges on the electric surface charge of the microfluidic device. Typically, silicon dioxide (or glass) surface is negatively charged due to deprotonated silanol groups. When this surface comes in contact with a solution containing ions, positive ions will be attracted to the surface forming an immobile layer and a diffuse layer (thickness on the order of nanometers, e.g. 100 nm for a 10^{-5} M NaCl solution) on the surface [1]. If an electric field is applied the diffuse layer (positive ions) will move along the field. Consequently, the rest of the fluid is dragged by this diffuse layer, via shear stress, resulting in a bulk motion. This is known as electro-osmotic flow (EOF) [2]. Electrokinetic micro-pumps make use of this mechanism to drive fluid flows, and can generate pressure up to 20 atm [3].

Apart from micro-pumps, vortex motion is another important feature for microfluidic devices. One of the potential applications is microscale mixing of fluids. Whereas homogeneous surface charge can be applied to fabricate micro-pumps, inhomogeneous surface charge can be used to generate vortical motion. In-plane vortices have been generated in a diffuser/nozzle configuration [4]. However, this approach still relies on both pressure gradient and EOF to generate bi-directional flows. Bi-directional and out-of-plane vortex flows, based on EOF, were generated with longitudinal and transverse surface charge patterns [5]. Other patterning techniques used based on a laminar flow of a coating solution [6] and micromolding [7], which are not convenient for batch fabrication.

In this work, surface charge pattern generated using a standard photolithography process is introduced. Since the pattern is defined by a photomask, virtually any positive or negative surface charge pattern can be realized. Preliminarily, experiments with simple longitudinal and transverse patterns are studied to generate two basic flows: bi-directional shear and out-of-plane vortex motion.

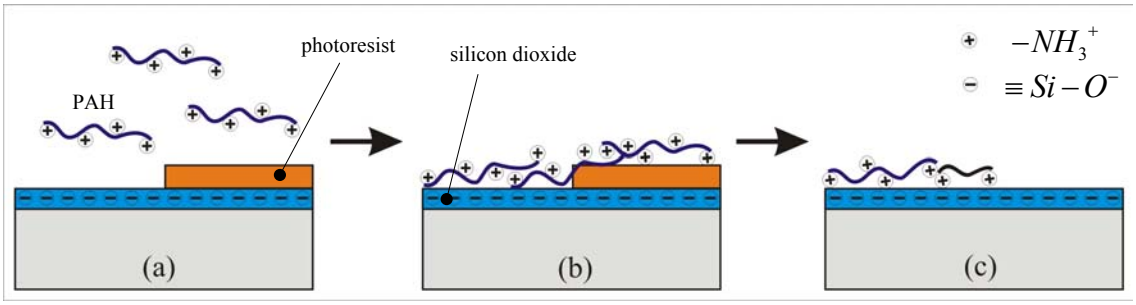
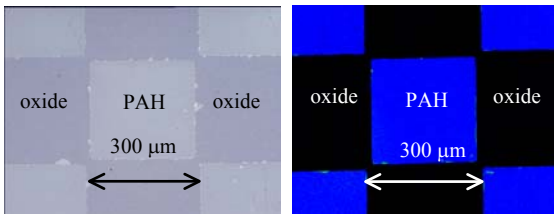


Figure 1. *A schematic illustration of the surface treatment process for silicon substrate: (a) incubation of the patterned PR wafer in the PAH solution, (b) wafer after PAH coating, and (c) wafer after PR strip.*

SURFACE CHARGE PATTERNING TECHNIQUE

In our work, negatively charged silicon dioxide or glass surfaces patterned with a positively charged polyelectrolyte were used. The negative surface charge is a natural phenomenon on silicon dioxide or glass surfaces due to deprotonated silanol groups. The positive surface charge is produced by coating the surface with polyalylamine (PAH) [8,9]. The methodology, for obtaining desired patterns of surface charge, involves selective coating at areas defined by standard photolithography. Glass (Corning 7740, Corning, USA) and silicon wafers of 4" in diameter were used as substrates. The fabrication process for both substrates was similar, except that a thermal silicon dioxide film was first grown on the silicon wafer prior to the coating procedures.

The wafer was treated with 1 % (wt%) sodium hydroxide (NaOH), at boiling temperature for 30 min, to generate silanol-salt groups (≡Si–ONa) at the surface. The sodium ions were then replaced by hydrogen ions using a treatment in 3 % (vol.) hydrochloric acid (HCl) to produce silanol groups (≡Si–OH). When these silanol groups are deprotonized in water, they carry negative charges. Photoresist (PR) was next spin coated onto the washed and dried wafer and patterned using a standard photolithography process. The wafer with the PR pattern was submerged into a solution of 15 mg ml^{-1} PAH in 0.01 M NaCl at pH 6 for about 10 hours at room temperature, Figure 1a. The PAH had previously been conjugated with fluorescein for inspection purposes. Positively charged PAH was deposited onto the substrate and PR surface, Figure 1b. Finally, the photoresist was removed in acetone for 15 min and then with ethanol, Figure 1c, to expose the negatively charged substrate surface.

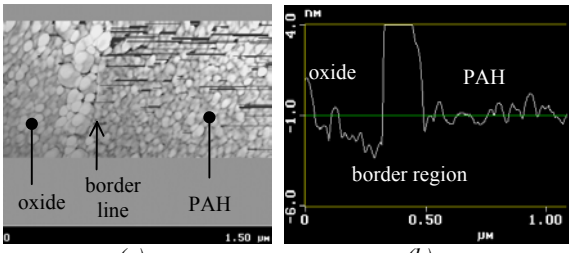


(a) (b)

Figure 2. *Patterns of PAH on silicon dioxide surface after PR removal. (a) light microscopy (b) fluorescent confocal scan (false color, the PAH-fluorescein is blue).*

A test pattern of the proposed technology is shown in Figure 2. The light microscopic image seen in Figure 2a corresponds to the pattern of the mask. Taking advantage of the PAH conjugation with fluorescein, PAH coating can be verified using fluorescence confocal scanning (ScanArray 5000, Packard Bioscience, USA). In this technique, only areas successfully coated with PAH will emit light, upon appropriate excitation, while the other areas will stay dark. The bright areas shown in Figure 2b correspond to the areas not protected by PR during the coating treatment. This image demonstrates the coating in the desired areas and that the removal of PR in acetone does not damage the coated surface.

Atomic force microscopy (AFM) was used to study the surface morphology and film thickness (Nanoscope, Digital Instruments, USA). The modified surface texture due to the coating is demonstrated in the AFM image shown in Figure 3a. The corresponding surface profile is shown in Figure 3b, where the thickness of the PAH layer is estimated to be about 2 nm. The modified properties of the coated surface can be visualized by their wetting characteristics as shown in Figure 4.



(a) (b)

Figure 3. *(a) AFM image of the boundary region of PAH-coating on silicon dioxide surface and (b) the corresponding AFM profile showing that the thickness of the PAH coating is about 2 nm.*

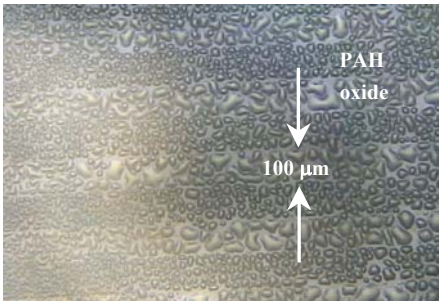


Figure 4. *Light microscopic image of a longitudinal pattern on a glass substrate. Small water droplets are seen on PAH coated stripes while bigger water droplets are seen on uncoated glass surface stripes.*

MICRO-CHANNEL CONFIGURATION AND EXPERIMENTAL SETUP

After patterning the surface charge, the glass wafer was diced into 20 mm × 30 mm in dimension.

Dice having the same pattern, either longitudinal or transverse, were bonded together by double side adhesive tape spacer to form a microchannel of rectangular cross-section. Each microchannel measures 50 μm in height, 30 mm in length and 10 mm in width.

Two platinum wire electrodes were placed at both ends of the microchannel. The channel was filled with deionized water (for minimizing the number of ions flowing within the fluid) and an electrical field was generated by the application of an electrical potential (100 V) on the electrodes. The resulting electric current was low enough to avoid excessive heating of the water.

In order to visualize the evolving flow patterns, polystyrene micro-particles of 1.8 μm in diameter were injected into the microchannel. The experiments were performed under a light microscope, which was connected to a video recording system through a CCD camera.

RESULTS AND DISCUSSION

In the longitudinal configuration, the surface charge pattern on the microchannel top and bottom surfaces is symmetric as shown in Figure 5. The pattern consists of alternate stripes, each 100 μm wide, aligned parallel to the microchannel axis. The stripes of silicon oxide surface carry negative charges, while the stripes of PAH carry positive charges.

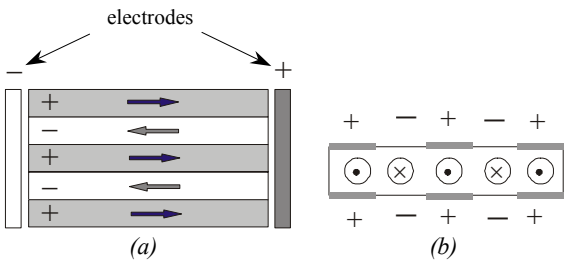


Figure 5. *Schematics of bi-directional shear flow in the micro-channel of longitudinal pattern. (a) top view and (b) side view seen from the positive electrode*

Positive ions in the mobile layers (diffuse layers) are attracted to the silicon dioxide surface, whereas the negative ions in the mobile layers are attracted to the PAH-coated surface. When the electric field was generated along the microchannel, the positive mobile ions in the diffuse layer of the oxide area moved to the negative electrode. Similarly, the negative mobile ions in the diffuse layer of PAH coated surface moved to the positive electrode. The resulting EOF pattern is a bi-directional shear flow as illustrated in Figure 5. The corresponding light microscopic image of the shear flow pattern is shown in Figure 6. Since the polystyrene particles are negatively charged in water, they are electrostatically attracted to positively charged surfaces. Indeed, the 100 μm wide PAH stripes are recognized as the regions with higher particle density. A sharp and stable boundary in this bi-directional shear flow is established. The speed of the particles in both regions was measured to be 150 μm s^{-1}. The particles stopped almost instantly when the electrical potential was switched off. Reversal of the electric field resulted in flow reversal with exactly the same bi-directional pattern and the same speed.

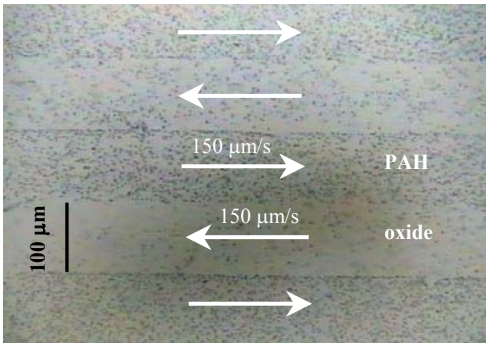


Figure 6. *Light microscopic image of the shear flow pattern illustrated schematically in Figure 5.*

In the transverse configuration, the surface charge pattern on the microchannel top and bottom surfaces is anti-symmetric as shown in Figure 7. The pattern consists of alternate stripes, each 200 μm wide, aligned perpendicular to the microchannel axis.

When an electric field was applied, the resulting EOF pattern is out-of-plane vortices with axes of rotation perpendicular to the electric field and parallel to the charged stripes as illustrated in Figure 7. Particles moving forward and backward within each stripe were observed Figure 8. These periodic motions were actually circular motions of microparticles in the vortex. Two images confirming the existence of the counter-rotating vortices are shown in Figure 8. In Figure 8a, the microscope focus was near to the channel bottom surface, showing the higher particle concentration above the alternate PAH stripes. In Figure 8b, the microscope focus was near to the top surface, showing similar concentration pattern corresponding to the alternate PAH stripes. The patterns in the pictures are out-of-phase as designed. Hence, the vortical flow in each cell was self-contained, and the sense of rotation was reversing upon reversal of the electric field direction.

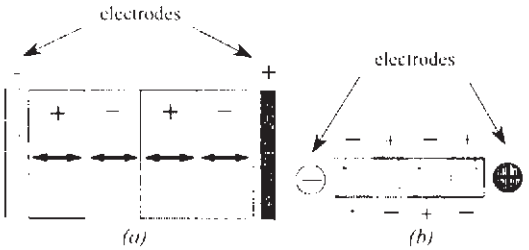


Figure 7. *Schematics of vortex orientation in a microchannel of transverse pattern. (a) top view and (b) side view.*

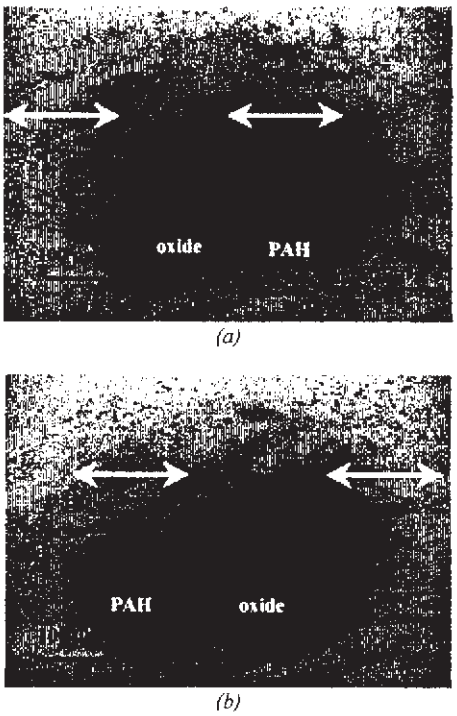


Figure 8. *Light microscopic images of vortices illustrated schematically in Figure 7. (a) focused at the bottom and (b) focused at the top of the microchannel.*

CONCLUSION

A new technology of patterning the surface charges on silicon dioxide or glass surface has been developed. Selective coating of polyelectrolyte (PAH) carrying positive charges has been demonstrated using standard photolithography techniques. Together with the negatively charged silicon dioxide or glass surface, virtually any combination of positive and negative charge pattern can be created. In this first attempt, longitudinal and transverse patterns were realized. Microchannels with these patterns were fabricated. Polystyrene particles were used to visualize the flow patterns. As designed, a bi-directional shear flow in the longitudinal pattern and an out-of-plane vortical flow in the transverse pattern were generated electro-kinetically under an applied electric field.

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REFERENCES

[1] Robert J. Hunter, *Zeta Potential in Colloid Science: Principles and Applications*, Academic Press, 1981.

[2] Paul D. Grossman and Joel C. Colburn, *Capillary Electrophoresis: Theory and Practice*, Academic Press, 1992.

[3] Shulin Zeng, Chuan-Hua Chen, James C. Mikkelsen, Jr., and Juan G. Santiago, *7th Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems*, Vol. 2, pp.31-6, 2000.

[4] G. L. Lettieri and E. Verpoorte, N. F. de Rooij, *11th Int. Conf. Solid-State Sensors Actuators*, pp.1510-1513, 2001.

[5] Abraham D. Stroock, Marcus Weck, Daniel T. Chiu, Wilhelm T. S. Huck, Paul J. A. Kenis, Rustem F. Ismagilov, and George M. Whitesides, *Physical Review Letters*, Vol. 84, no. 15, pp. 3314-3317, 2000.

[6] Paul J. A. Kenis, Rustem F. Ismagilov and George M. Whitesides, *Science*, Vol. 285, pp. 83-85, 1999.

[7] Noo Li Jeon, Insung S. Choi, Bing Xu, and George M. Whitesides, *Adv. Mater.*, Vol. 11, no. 11, pp. 946, 1999.

[8] Bertrand P., Jonas A. and Laschewsky A. Legras R., *Macromolecular Rapid Communications*, vol. 7, pp. 21, 2000.

[9] K.M. Chen, X. Jiang, L.C. Kimerling and P.T. Hammond, *Langmuir*, vol. 16, pp. 7825-7834, 2000.